May 2002 • NREL/CP-520-31405

Conference Paper

What is the Appropriate Reference Spectrum for Characterizing Concentrator Cells?

Preprint

K. Emery, D. Myers, and S. Kurtz

To be presented at the 29th IEEE PV Specialists Conference
New Orleans, Louisiana
May 20-24, 2002

National Renewable Energy Laboratory

1617 Cole Boulevard
Golden, Colorado 80401-3393

NREL is a U.S. Department of Energy Laboratory
Operated by Midwest Research Institute • Battelle • Bechtel

Contract No. DE-AC36-99-GO10337

Available electronically at http://www.osti.gov/bridge

Available for a processing fee to U.S. Department of Energy
and its contractors, in paper, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone: 865.576.8401
fax: 865.576.5728
email: reports@adonis.osti.gov

Available for sale to the public, in paper, from:
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
phone: 800.553.6847
fax: 703.605.6900
email: orders@ntis.fedworld.gov
online ordering: http://www.ntis.gov/ordering.htm

Printed on paper containing at least 50% wastepaper, including 20% postconsumer waste

WHAT IS THE APPROPRIATE REFERENCE SPECTRUM FOR CHARACTERIZING CONCENTRATOR CELLS?

Keith Emery, Daryl Myers, and Sarah Kurtz
National Renewable Energy Laboratory (NREL), 1617 Cole Blvd., Golden, CO 80401

ABSTRACT

Consensus standards for determining the efficiency of a concentrator cell or module have not been developed. NREL, Sandia National Laboratory, the Fraunhofer Institute for Solar Energy in Germany, and the Progress in Photovoltaics Efficiency Table authors have informally agreed upon concentrator-cell reference conditions. These conditions are 25°C cell temperature, 1-sun = 1000 W/m^2 total irradiance, and the ASTM E891-87 direct-normal reference spectrum. Deficiencies in the direct reference spectrum are discussed, and a more representative reference spectrum for evaluating concentrator cells is proposed. The spectrum was generated by the SMARTS model, and the atmospheric parameters are as close as possible to the existing direct spectrum, with the exception that the aerosol optical depth at 500 nm is reduced from 0.27 to 0.085.

REVIEW OF EXISTING REFERENCE CONDITIONS

Consensus standards were first proposed at the first and second terrestrial Photovoltaic Measurement Procedures Workshop in 1976 and documented in the Terrestrial PV Measurements Procedures [1-3]. The manual specified equipment and procedures for measurement of light I-V curves for one-sun and concentrator cells and modules [3]. For measurement of concentrator cells, the manual specified a direct-beam reference spectrum, a one-sun irradiance of 1000 W/m^2, a temperature of 28°C, and an area defined as the area that is designed to be illuminated, which is normally the total area minus any peripheral bus bars or contacts [3]. For concentrator modules, the area was taken to be the cross-sectional area of the lens or mirror receiver. For the direct-beam reference spectrum, the atmospheric parameters were 2 cm precipitable water vapor, a turbidity of 0.12, an air mass (AM) of 1.5, and 0.34 cm of ozone [3]. The 1977 model was rather crude and was regenerated for global and direct conditions using a Monte Carlo computer model [4]. This new rigorous model was based on the United States Standard Atmosphere Mid-Latitude Summer profile, with 1.416 cm of precipitable water vapor and an ozone level of 0.344. An air mass of 1.5 at sea level with a sun–facing surface tilted at 37° and a wavelength-independent ground reflectivity of 0.2 were chosen [4].

The simplistic aerosol profile in the original reference spectrum [3] was difficult to reproduce and contained several errors in implementation. A rural aerosol profile was chosen in the rigorous model, and it corresponded to an aerosol optical depth at 500 nm of 0.27 or a visibility of 23 km. The choice of 0.27 for the turbidity was based on limited resource information, but was intended to be an average value in the continental United States and not an average value in locations where concentrators might be deployed. The results from the Monte Carlo model in Reference 4, along with the data from an undocumented simple model, were then incorporated into standards [5-7]. These standards have been in use by the photovoltaics community since about 1985.

Reference conditions for rating concentrator cells and modules have been informally agreed upon by NREL, Sandia National Laboratory, the Fraunhofer Institute for Solar Energy in Germany, and the Progress in Photovoltaics Efficiency Table authors [8]. These conditions are 25°C cell temperature, one-sun = 1000 W/m^2 total irradiance, and the ASTM E891-87 direct-normal reference spectrum in Reference 7. Concentrator modules and systems have been rated at PVUSA with respect to their performance at a direct-normal irradiance of 850 W/m^2, 1 m/s wind speed, and an air temperature of 20°C [9]. Consensus standards for concentrator measurements are currently under development in the United States and Europe.

MOTIVATION FOR CHANGING DIRECT REFERENCE SPECTRUM

The U.S. Department of Energy (DOE) High-Performance PV Project calls for a 33% concentrator module and a 40% concentrator cell to be developed [10]. The reference conditions to be used for measuring these efficiencies need to be clearly defined.

Recent work has shown that the direct reference spectrum is not representative of sunny conditions in regions with a high annual direct-normal energy where concentrators might be deployed (the Sun Belt). In the past, this issue did not matter because at a given total irradiance and cell temperature under direct, global, or clear-sky natural sunlight, concentrator PV cells or modules produced the same short-circuit current within ±2%. The reason stems from the fact that in the past, the only concentrator cells were single-junction Si, GaAs, or independently measured multijunction cells that have a small spectra sensitivity. In contrast, the short-circuit current of the series-connected GaInP/GaAs/Ge triple-junction cells are much more sensitive to spectral variations. The highest efficiency cell measured at NREL was 34.0±1.5% for solar fluxes between about 130 and 630 suns under the IEC global reference spectrum [5,6] and

30.7±1.5% under the ASTM E891-87 direct reference spectrum [7]. Reference conditions should provide a basis for optimizing energy production of cells in the field. A recent study using standard reference days shows that GaInP/GaAs cells optimized for the direct spectrum produce 1% to 3% less electricity than cells optimized for daily energy [11]. The direct spectrum predicts 7% less power at solar noon for the hot-sunny reference day compared with 1% for the global spectrum [11].

This sensitivity to spectrum becomes problematic if the indoor measurement spectrum differs significantly from the spectra that are typically observed outdoors. The PVUSA procedure for outdoor characterization of concentrator modules has no provisions for correction to a given reference spectrum. This means that concentrator modules evaluated at direct irradiances greater than 850 W/m^2 are being rated under conditions more representative of the IEC global spectrum or the direct spectrum with a more representative turbidity. Most of the test locations for concentrator modules encounter direct spectra that are substantially different from the existing direct reference spectrum.

Changing standard reference conditions is problematic and should not be taken lightly. In the early 1980s, there were a wide range of “AM1.5” spectra that various groups around the world referred to, giving a spread in short-circuit currents of 3% to 9%, depending on the spectra and PV technology [12]. The world is now in agreement for the standard reference spectra for evaluating nonconcentrating cells and modules at the national (U.S., Japanese, and European Commission standards) and international (IEC standards) level. This is not the case for concentrators.

This paper discusses the technical basis for the new proposed direct reference spectrum and its effect on the short-circuit current. NREL will adopt this spectrum for evaluating concentrator cells and submit it to various standards organizations for consideration.

SELECTION OF DIRECT-BEAM REFERENCE CONDITIONS

The justification for AM1.5 as the appropriate air mass for rating concentrator performance has never been published. Figure 1 shows that 50% of the direct-beam annual energy derived from the TMY2 data base is delivered at an absolute (pressure-corrected) air mass of 1.5 for many locations [13]. This validates the choice of AM1.5 as the reference air mass. Note that sunny locations such as Boulder, Colorado or Albuquerque, New Mexico have 20% of the direct beam energy delivered at an absolute or pressure-corrected air mass less than 1.

Current aerosol information is more comprehensive and more accurate than the information used in the BRITE comprehensive computer model to generate the current reference spectra [14,15]. Figure 2 shows the region of the United States that was selected to determine the average turbidity to use in modeling the proposed direct reference spectrum. Sites in the continental United States with a daily direct beam energy greater than 6 kWh/m^2/day were selected. In Table 1 the aerosols for the selected sites used to arrive at a broadband aerosol optical depth of 0.0565 are given. The aerosol optical depth at 500 nm is required for spectral modeling purposes and was determined using the procedure described in Reference 15.

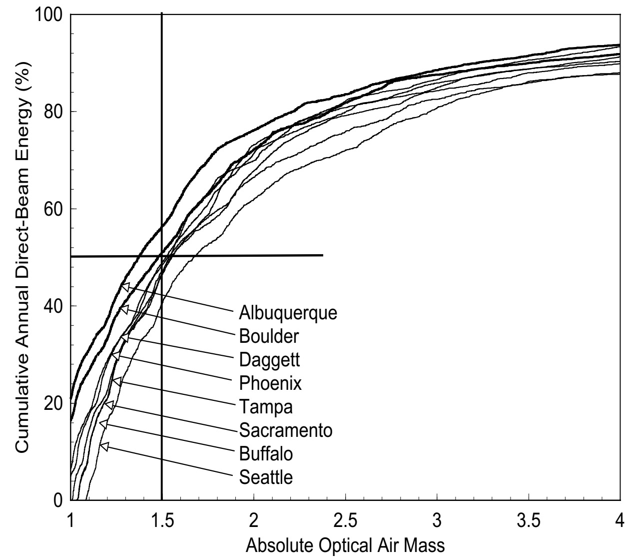

Fig. 1. Cumulative annual direct-beam energy from TMY2 data base. Note that for Colorado and New Mexico, 20% of the energy is delivered below air mass 1.

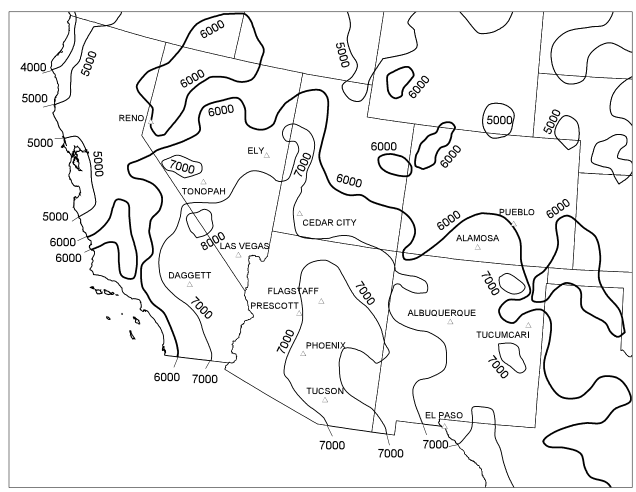

Fig. 2. Region of the United States where the average daily direct-beam energy is greater than 6 kWh/m^2/day has an average broadband aerosol optical depth of 0.0565, corresponding to an aerosol optical depth at 500 nm or turbidity of 0.085.

Table 1. Sites used to determine the average aerosol optical depth in the sunbelt [14,15]. Data was collected at the prime sites and modeled using the METSTAT model [15].

AOD @500 nm	AOD broad band	Station	E_{tot} kWh/m^2/day	type
0.087	0.058	Daggett, CA	7.50	prime
0.105	0.068	Las Vegas, NV	7.10	prime
0.099	0.065	Tucson, AZ	7.00	prime
0.142	0.090	Phoenix, AZ	6.80	prime
0.074	0.050	Prescott, AZ	6.80	model
0.029	0.024	Alamosa, CO	6.80	prime
0.074	0.050	Albuquerque, NM	6.70	prime
0.082	0.055	Tonopah, NV	6.70	model
0.118	0.076	El Paso, TX	6.70	prime
0.074	0.050	Flagstaff, AZ	6.40	model
0.091	0.060	Reno, NV	6.20	model
0.074	0.050	Cedar City, UT	6.20	model
0.074	0.050	Pueblo, CO	6.10	model
0.099	0.065	Tucumcari, NM	6.10	model
0.050	0.036	Ely, NV	6.00	prime
<0.085>	<0.056 >			

A comprehensive computer model was used to generate the revised spectrum and has been compared against other comprehensive models [16-18]. Figure 3 compares the existing global and direct reference spectra with the proposed direct spectrum. The proposed direct spectrum uses the same meteorological parameters as the existing reference spectra but with the lower aerosol optical depth of 0.085 at 500 nm. Figure 4 shows the percentage variation in the short-circuit current for the proposed direct spectrum, the existing direct spectrum, and the proposed global reference spectrum, compared with the existing global reference spectrum. The quantum efficiencies used in calculating the short-circuit current densities in Figure 4 are given in Figures 5 and 6. As expected, the variation for single-junction devices is much less than the variation for multijunction devices. The global spectrum corresponding to the proposed direct spectrum affects the short-circuit current for all relevant PV technologies less than ±1% compared to the existing global reference spectrum.

SUMMARY

The justification for rating concentrator cells at an aerosol optical depth (AOD) typical of the sunbelt instead of the 0.27 AOD at 500 nm is given. The corresponding direct spectrum is more realistic for optimizing concentrator modules for maximum energy production over the entire day, and especially near solar noon, based on modeling work presented elsewhere at this conference [11]. The spectrum can be obtained by sending an email to keith_emery@nrel.gov. Procedures for evaluating concentrator modules have not been standardized and are an active area of research. In the meantime, procedures for rating concentrator modules will follow procedures developed by PVUSA, Sandia, and other groups.

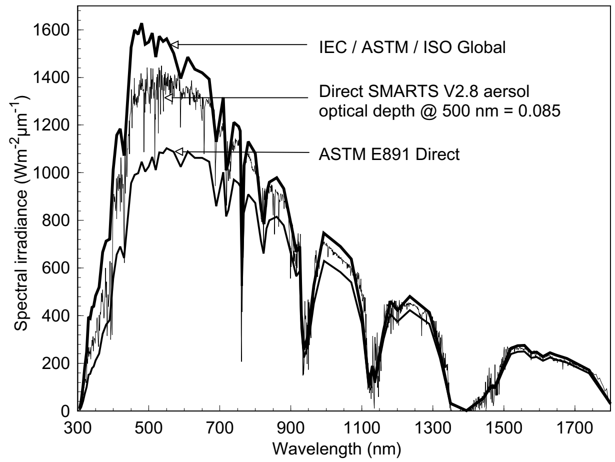

Fig. 3. Proposed direct reference spectrum compared with the current global and direct reference spectra.

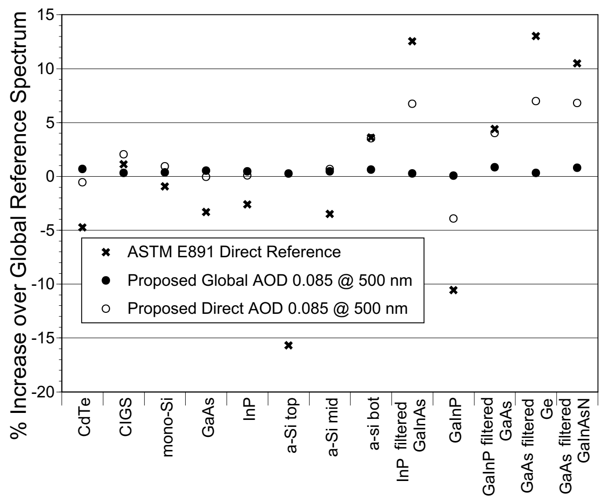

Fig. 4. Percentage change in the normalized short-circuit current from the normalized global reference spectrum for various state-of-the-art PV technologies compared with the proposed direct reference spectra.

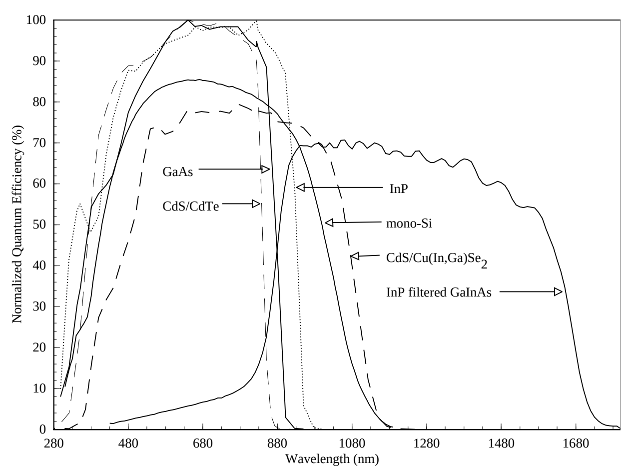

Fig. 5. Quantum efficiencies used for six of the PV technologies in Figure 4.

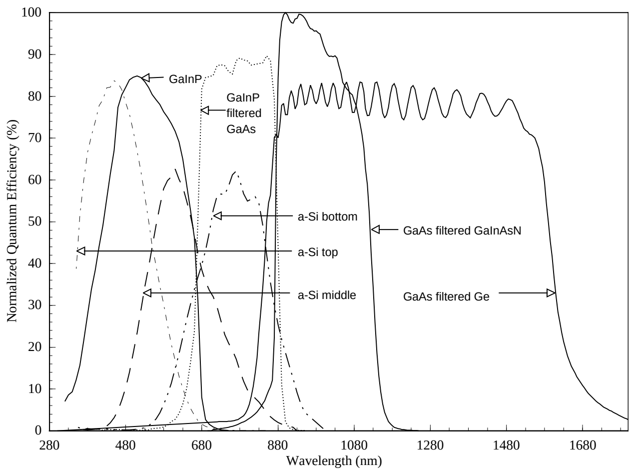

Fig. 6. Quantum efficiencies used in calculating the short-circuit current densities for the remaining seven PV technologies in Figure 4.

ACKNOWLEDGEMENTS

This work was supported in part under DOE Contract DE-AC36-99GO10337. The authors also wish to acknowledge the encouragement of R. Hulstrom and M. Symko-Davis. The assistance of D. Heimiller in producing the resource maps and of M. Forest and D. Gwinner for editing is acknowledged.

REFERENCES

[1] Terrestrial Photovoltaic Measurements Workshop Proceedings, Cleveland, OH, March 15-21, 1975, L. Scuddre and T. Klucher editors, NASA tech. rep. TM X-71802.

[2] Terrestrial Photovoltaic Measurements Workshop Proceedings, Baton Rouge, LA, Nov. 10-12, 1976, ERDA/NASA-1022/76/10.

[3] Terrestrial Photovoltaic Measurement Procedures, NASA Tech. Report TM 73702, June 1977.

[4] R.E. Bird, R.L. Hulstrom, and L.J. Lewis, (1983), "Terrestrial Solar Spectral Data Sets," *Solar Energy*, **39**, p. 563.

[5] Standard IEC 60904-3, Measurement Principles for Terrestrial PV Solar Devices with Reference Spectral Irradiance Data, International Electrotechnical Commission, (1989), Geneva, Switzerland.

[6] Standard ASTM E892-92, *Standard for Terrestrial Solar Spectral Irradiance Tables at Air Mass 1.5 for a 37° Tilted Surface*, Amer. Society for Testing Matls., West Conshocken, PA, USA.

[7] Standard ASTM E891-92, *Standard for Terrestrial Solar Direct Normal Solar Spectral Irradiance Tables for Air Mass 1.5*, Amer. Society for Testing Matls., West Conshocken, PA, USA.

[8] M.A. Green and K. Emery, D.L. King, S. Igari, and W. Warta, "Solar Cell Efficiency Tables (version 19)," *Progress in PV Research and Applications*, **vol. 10**, p. 55, 2002.

[9] S.L. Hester, T.U. Townsend, W.T. Clements, and W.J. Stolte, (1990), PVUSA: Lessons Learned from Startup and Early Operation, *Proceedings of the 21st IEEE PV Specialists Conf.*, Orlando, pp. 937.

[10] M. Symko-Davis, R. Noufi, and S. Kurtz, "Identifying Critical Pathways for High-Performance PV," this conference.

[11] W. E. McMahon, S. Kurtz, K. Emery, and M. Young, "Criteria for the Design of GaInP/GaAs Tandem Cells, to Optimize Their Performance Outdoors," this conference.

[12] N.M. Pearsall, K.A. Emery, and M. Davies, "Influence of Reference Cell and Spectrum on the Measurement of Solar Cells," *Proc. 7th Eur. PV Solar Energy Conf.,* Oct. 27-31,1986, p. 298.

[13] W. Marion and K. Urban, "Users' Manual for TMY2s (Typical Meteorological Years)-Derived from the 1961-1990 National Solar Radiation Database, NTIS/GPO number: DE950040604," National Renewable Energy Laboratory, Golden, Technical TP-463-7688, 1995.

[14] E.L. Maxwell, W. Marion, D. Myers, M. Rymes, and S. Wilcox, "Final Technical Report – National Solar Radiation DataBase (1961-1990)," National Renewable Energy Laboratory, Golden, CO, NREL/TP-463-5784, 1995.

[15] E.L. Maxwell, (1998). "METSTAT The Solar Radiation Model Used in the Production of the National Solar Radiation DataBase (NSRDB)." *Solar Energy* **62**(4): 263-279.

[16] Gueymard, C. (2001). "Parameterized Transmittance Model for Direct Beam and Circumsolar Spectral Irradiance." *Solar Energy* **71**(5): 325-346.

[17] D. Myers, K. Emery, and C. Gueymard, "Proposed Reference Spectral Irradiance Standards to Improve Photovoltaic Concentrating System Design and Performance Evaluation," this conference.

[18] D. Myers and K. Emery, "Terrestrial Solar Spectral Modeling Tools and Applications for Photovoltaic Devices," this conference.

REPORT DOCUMENTATION PAGE			*Form Approved OMB NO. 0704-0188*
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.			
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE May 2002	3. REPORT TYPE AND DATES COVERED 29th IEEE PVSC-Conference Paper May 20-24, 2002	
4. TITLE AND SUBTITLE What Is The Appropriate Reference Spectrum For Characterizing Concentrator Cells?: Preprint			5. FUNDING NUMBERS PVP23401
6. AUTHOR(S) K. Emery, D. Myers, and S. Kurtz			
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393			8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) National Renewable Energy Laboratory 1617 Cole Blvd. Golden, CO 80401-3393			10. SPONSORING/MONITORING AGENCY REPORT NUMBER NREL/CP-520-31405
11. SUPPLEMENTARY NOTES			
12a. DISTRIBUTION/AVAILABILITY STATEMENT National Technical Information Service U.S. Department of Commerce 5285 Port Royal Road Springfield, VA 22161			12b. DISTRIBUTION CODE
13. ABSTRACT *(Maximum 200 words)* This conference paper describes Consensus standards for determining the efficiency of a concentrator cell or module that have not been developed. NREL, Sandia National Laboratory, the Fraunhofer Institute for Solar Energy in Germany, and the Progress in Photovoltaics Efficiency Table authors have informally agreed upon concentrator-cell reference conditions. These conditions are 25ºC cell temperature, 1-sun =1000 W/m2 total irradiance, and the ASTM E891-87 direct-normal reference spectrum. Deficiencies in the direct reference spectrum are discussed, and a more representative reference spectrum for evaluating concentrator cells is proposed. The spectrum was generated by the SMARTS model, and the atmospheric parameters are as close as possible to the existing direct spectrum, with the exception that the aerosol optical depth at 500 nm is reduced from 0.27 to 0.085.			
14. SUBJECT TERMS: PV; concentrator cell; module; cell temperature; direct-beam reference spectrum; one-sun irradiance; aerosol optical depth; short –circuit current; global reference spectrum; multijunction devices;			15. NUMBER OF PAGES 16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102